Biological Services Program

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Air Pollution and Acid Rain,
Report No. 2

Potential Impacts of Low pH on Fish and Fish Populations

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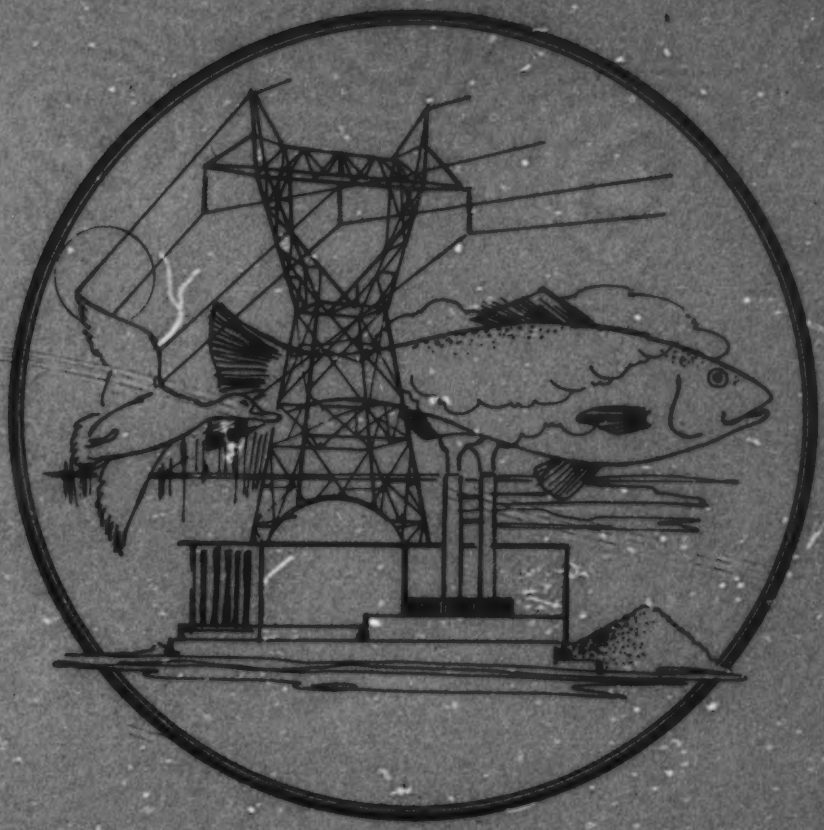

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2. To gather, analyze, and present information that will aid decision makers in the identification and resolution of problems associated with major land and water use changes.

3. To provide better ecological information and evaluation for Department of the Interior development programs, such as those relating to energy development.

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Biological Services Program

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Air Pollution and Acid Rain,
Report No. 2

POTENTIAL IMPACTS OF LOW PH ON FISH AND FISH POPULATIONS

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PREFACE

The passage of the Clean Air Act and its 1977 Amendments resulted in a number of regulations to protect air quality. Incorporated in this legislation is a new responsibility for federal land managers, including the Fish and Wildlife Service, to assess and evaluate impacts of air quality degradation on "air quality related values" on certain lands under their jurisdiction. Inherent in meeting this responsibility is the need for comprehensive and current information on ecological effects of air pollution, including acidic precipitation.

Since the early 1970's ecological research in air pollution and acid rain has steadily increased and a number of ecosystem scale studies have been initiated. As the results of these studies and other topical research become available, the need exists within the Service and other groups for analysis, interpretation, and concise summaries of this information as it relates to the potential impacts to fish and wildlife resources. Potential Impacts of Low pH on Fish and Fish Populations addresses this need in part by providing up-to-date information in a format appropriate to fishery resource evaluation. The report is intended to assist biologists and decision makers in assessment of ecological impacts and enable their effective input into the regulatory process.

Suggestions or comments regarding the report should be addressed to:

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ABSTRACT

Descriptions of the effects of low pH on fish are presented. Subject areas are identified in which further studies are needed. Laboratory experiments show that the toxic effect of low pH differs among species, populations, and age-groups of the same species. Field studies show that the toxicity of low pH is compounded by other water characteristics. Evidence from a number of laboratory and field studies indicate that low pH could increase susceptibility to disease, impair osmoregulation and ionregulation, inhibit hormone production or activity, result in genetic damage, change predator-pray relationships, degrade habitat, and increase the availability of toxic substances. Low pH is shown to result in reproductive failure on the population level, recruitment failure, and on the individual level, cessation of spawning. Slight declines in productivity as they relate to stressed populations, are shown to have the potential to result in unrecoverable drops in population density.

INTRODUCTION

A great deal of interest has recently arisen concerning the environmental impacts associated with increasing acidification of surface waters, particularly as this relates to acid precipitation. One of the most alarming impacts associated with this phenomenon is the decline and extinction of fish populations and assembleges in a large number of lakes in the Adirondack Mountains of New York, the La Cloche Mountains of Ontario, and the lakes and streams of southern Norway and western Sweden. A growing body of information suggests that other areas of the United States and eastern Canada are susceptible and may experience similar damage from acidification.

Much scientific activity presently is being devoted to identifying the ecological processes that are instrumental in lake acidification. Comparatively little effort is being made to identify and assess pH-related mechanisms that could affect fish populations.

This paper identifies a number of acid-induced stresses that either alone, or associated with other man-induced stresses (e.g., fishing pressure and contaminants), could result in population extinction. Subject areas on which further study is warranted are also suggested.

DIRECT MORTALITY

Fish mortality induced by acidified water has been attributed to anoxia (suffocation), depletion of body sodium, and lowered blood pH (Packer and Dunson 1972). Most chemical reactions are pH sensitive, consequently a high probability exists that pH-related mortality results from modification of many physiological processes (Fromm 1980). Further research is needed before we will know which processes are affected and how the effects are expressed.

LABORATORY STUDIES

Experimental evidence shows that the toxic effects of pH differ among species, populations, and age groups of the same species (Table 1). Water

Table 1. Range of pH Toxicity among Species, Populations, and Life Stages of the Same Species. (pH levels are the lowest presented in each cited publications).

Species	Location	Life Stage	pH	Investigators
Brook trout (*Salvelinus fontinalis*)	Canada (N.S.)[1]	Fingerling	3.5	Daye and Garside (1975)
	U.S.A. (W.V.)[2]	Adults	4.5	Menendez (1976)
	U.S.A. (W.V.)	Alevins	5.0	Menendez (1976)
Atlantic Salmon (*Salmo salar*)	Norway	Eggs, alevins	5.0-5.5	Wright et al. (1975)
	Canada (N.S.)	Eggs	3.1-3.6	Daye and Garside (1977)
	Canada (N.S.)	Alevins	4.0	Daye and Garside (1977)
	England	Eggs	3.5	Carrick (1979)
Brown trout (*Salmo trutta*)	Norway (river)	Eggs, alevins	4.5	Wright et al. (1975)
	Norway (hatchery)	Eggs	4.7	Gjedrem (1976)
	England	Eggs	3.5	Carrick (1979)
	Norway	Adult	4.0	Leivestad and Muniz (1976)
	Norway (7 rivers)	Alevins	4.4-5.2	Grande and Anderson (1979)
Flag fish (*Jordanella flouidae*)	Canada	Adult	5.5	Craig and Baksi (1977)
	Canada	Egg and fry	5.0	Craig and Baksi (1977)
White suckers (*Entastomys commersoni*)	Canada	Adult	4.0	Beamish (1972)
Blue gill (*Lepomis gibbosus*)	U.S.A.	Adult	4.0	Trama (1954)
Fat head minnow (*Pimephales promelus*)	U.S.A.	Adult	4.0	Mount (1973)

[1] N.S. indicates Nova Scotia
[2] W.V. indicates West Virginia

below pH 4.5 is toxic to most species (Table 1). Most toxicity studies suggest that eggs and post-yolksac larvae are more tolerant than yolksac larvae; young-of-the-year are less tolerant than adults (Mount 1973; Menendez 1976; Craig and Baksi 1977; Daye and Garside 1977, 1979). Size does not always determine sensitivity even though small young fish appear to be more sensitive to low pH than are larger older fish. For example, pumpkinseed (Lepomis gibbosus) and yellow perch, (Perca flavescens) appear more resistant to low pH than the larger rainbow trout (Salmo gairdneri) and walleye (Stizostedion vitreum) (Beamish et al. 1975). Thus, differences in sensitivity to pH probably are determined by the ontology and physiology of the species rather than simply to size.

In toxicity studies test organisms have been continuously exposed to the particular pH level under investigation. Such tests are useful for identifying the limits of tolerance for a given species or age-class; however, they do not fully represent conditions a species may experience in the wild. For example, a major potential impact of acid precipitation on fish is exposure to lethal pH levels at the time of snowmelt and after a heavy rain. Leivestad and Muniz (1976) reported massive kills of salmon and trout in a Norwegian river during snowmelt and after heavy rain. They provide no information concerning the exposure time experienced by the affected species. Few studies have been conducted to determine how long a species must be exposed before a pH level is lethal. Similarly, few studies have attempted to determine latent and indirect mortality of short-term exposure to lethal levels of pH. Different life stages of fish have different responses to pH, thus, exposure time required to induce mortality may also differ among life stages. Studies on levels of exposure and length of time of exposure to depressed pH are critical because many fish species do not acclimate to changes in pH (Lloyd and Jordan 1964; Mount 1973; Daye 1980).

The time of the year that a species or life stage is exposed to lower than "natural" levels of pH may also affect survival. Fishes that have recently over wintered and are in a weakened physical condition may be more likely to succumb to pH stress than those that are in prime physical condition. Greater chances for acid induced mortality exist in the summer when some populations of fish might normally be under thermal stress (e.g., salmonids) and the frequency of heavy rain storms rich in sulfuric and nitric acid increases.

FIELD STUDIES

Laboratory results are not always directly applicable to field conditions. A number of studies show that toxicity of low pH is compounded by other water characteristics (EIFAC 1969; Giddings and Galloway 1976). For example, for fingerling rainbow trout in water containing 10 ppm free CO_2 the median lethal pH was 4.5. In water containing 20-ppm free CO_2 the lethal pH was 5.7 (Lloyd and Jordan 1964). Survival time for rainbow trout kept at constant pH was shown to decrease as calcium concentration decreases (Lloyd and Jordan 1964). Studies by Cronan and Schofield (1979) and Schindler et al. (1980) have shown how pH can affect the solubility of aluminum and thereby increase water toxicity. The synergistic toxicity of low pH, coupled with heavy metals and contaminants, is potentially more lethal than either component acting alone.

Although the pH in many lakes and streams in the U.S., Canada, and Scandinavia is 4.5 or below (Almer et al. 1974; Harvey 1975; Schofield 1976), little evidence exists that all individuals of a fish population are killed by a single catastrophic decline in pH. Lakes in which the extinction of fish communities has been observed show declines in stocks before lethal levels of pH are attained (Table 2). These declines may be attributed to increased mortality of younger life stages at pH levels higher than those lethal to adults. Thus, the population is almost extinct by the time pH falls to levels lethal to adults. More studies are required of the fish populations in acidifying lakes before accepting the scenario that extinction results from pH induced recruitment failure.

INDIRECT MORTALITY

Exposure to sublethal levels of low pH can also result in population extinction, increased susceptibility to natural causes of mortality, or reduced viability via important physical and biological components of the ecosystem or changes in the availability of toxic chemicals.

DISEASE

Changes in blood chemistry and macromolecules result from exposure to low pH (Falk and Dunson 1977; Fromm 1980) and destruction of the body's protective epithelial cells (Daye and Garside 1976) can reduce the ability of a fish to resist disease. In its review of the literature, the EIFAC (1969) reported the common belief among carp culturists that low pH increases the susceptibility to disease. Carp are reported to develop hypersensitivity to bacteria below a pH of 5.5 (EIFAC 1969). However, no controlled laboratory experiments demonstrating this effect could be found in the literature.

OSMOREGULATION AND IONREGULATION

The disturbance of normal ion balance, such as sodium depletion at lethal levels of pH (Packer and Dunson 1972), suggests that sublethal levels of pH can result in destruction or modification of osmoregulatory organs or processes in fish. Daye and Garside (1976) observed changes in gill lamellae (one of the major sites of osmoregulation) of brook trout at pH as high as 5.2. Partial failure of the osmoregulatory and ionregulatory tissues may not by themselves result in mortality, but the physiological stress resulting from ionic imbalance can adversely affect the organism's responses to its environment (e.g., increased susceptibility to predation, decreased feeding efficiency, and increased susceptibility to thermal stress).

ENDOCRINE IMBALANCE AND GENETIC DAMAGE

Low pH has been shown by many investigators to have an adverse effect on the production and viability of ova (Table 3). This effect suggests that pH can influence the endocrine system of maturing females or damage the genetic material of developing ova. Although studies have not been conducted to estimate the effects of pH on endocrine activity, decreased blood pH could because of the effect on macromolecules (Fromm 1980) inhibit hormonal production or activity. Similarly, studies have not been

Table 2. Approximate pH at which some Fish Species Stopped Reproduction and Population Density Began to Decline (Beamish 1976).

pH at which reproduction ceases	Species	Family
6.0+ to 5.5	Smallmouth bass *Micropterus dolomicui*	Centrarchidae
	Walleye *Stizostedion vitroum*	Percidae
	Burbot *Lota lota*	Gadidae
5.5 to 5.2	Lake trout *Salvelinus namaycush*	Salmonidae
	Troutperch *Percopsis omiscomnycus*	Percopsidae
5.2 to 4.7	Brown bullhead *Ictalurus nebulosus*	Ictaluridae
	White sucker *Catostomus commersoni*	Catostomidae
	Rock bass *Ambloplites rupestris*	Centrarchidae
4.7 to 4.5	Lake herring *Coregonus artedil*	Salmonidae
	Yellow perch *Perca flavescene*	Percidae
	Lake chub *Coucsius plumbeus*	Cyprinidae

Table 3. Compilation of Experimental Studies demonstrating the Effect of Depressed pH on the Number of Eggs Produced and Viability of the Eggs

Species	pH	Number of Eggs	% fertile eggs	Investigator
Flagfish (*Jordanella floridae*)	6.8	2467[a]	90.1	Craig and Baksi (1977)
	6.0	1277	78.6	
	5.0	557	68.0	
	4.5	1	0.0	
Brook trout (*Salvelinos fontinalis*)	6.5	732[b]	69.3	Menendez (1976)
	6.0	223	60.0	
	5.5	745	74.0	
	5.0	703	26.6	
	4.5	0	0	
Fathead minnows (*Pimephales promelas*)	7.5	968[b]	79	Mount (1973)
	6.6	210	78	
	5.9	101	55	
	5.2	0	-	
	4.5	0	-	

[a] total number of eggs produced by all females.
[b] the number of eggs produced by each female.

reported on genetic changes in ova maturing under acidic conditions. However, genetic damage may be a partial explanation of the reduced viability of ova produced by brook trout maintained at sublethal levels of pH (Menendez 1976).

CHANGES IN PREDATOR PREY RELATIONSHIPS

Declining numbers of preferred food items and subsequent shifting to food items less susceptible to acid stress could lead to increased predation on a species economically and recreationally important to man. Beamish (1976) has shown that many forage species (e.g., minnows and darters) become extinct at higher pH levels than many piscivorous species. As the prey species decline, larger, older predators may feed on young of other piscivores or on their own kind. Such a situation in a nonacified lake has been described for the yellow perch and walleye populations (Forney 1976).

HABITAT DEGRADATION

Hendrey (1976) and Müller (1980), in studying the effects of pH on the growth of periphytic algae, demonstrated that algal growth increases with a decline in pH. Gorhen and Gorden (1960, 1963 as reported in Giddings and Galloway 1976) note an impoverishment of the macrophyte communities in lakes of "low pH (3.2-6.1)" as compared to lakes of "high pH 4.4-7.4)." Increased growth of periphyton and changes in species composition of macrophytes can result in either degradation or improvement of aquatic habitats. Changes in composition and density of aquatic vegetation can be particularly serious for species that have relatively specific habitat requirement for spawning. For example, growth of periphyton on gravel within spring spawning areas of rainbow trout (Salmo gairdeneri) could impair spawning activity and hatching success of these fishes which require "clean" gravel for incubation.

Mosses have been shown to form dense mats that cover benthic substrates in acidified freshwater in Scandinavia (Grahn et al. 1974). Sphagnum moss was shown by Hendrey (1976) to be the most abundant macrophyte in acidified lakes of Scandinavia. The occurance of Sphagnum has recently been reported in acidified Adirondack lakes (Hendrey, Personal Communications). At pH 5.2, aquatic habitats can be further degraded through the partial inhibition of bacterial decomposition of organic debris and increased fungal growth (Wright et al. 1975), which results in the covering of lake and stream bottoms with organic debris and fungal mats.

CHANGE IN AVAILABILITY OF TOXIC SUBSTANCES

A closely related effect of increased acidity is increased solubility of certain harmful chemicals. As previously stated, increased acidity appears to increase the solubility of aluminum which is potentially toxic to fish. Schindler et al. (1980) demonstrated that at a pH of 5.0 and 6.0, aluminum, manganese, zinc, and iron are released from lake sediments. Such releases, along with imput from increased leaching from a surrounding watershed and direct atmospheric deposition, could potentially increase the concentration of toxic chemicals to levels that are deletarious to the health of fish populations of the receiving water body.

REPRODUCTIVE FAILURE

Reproductive failure in fish is probably the single most significant effect of increased acidity in freshwater ecosystems. Most of the evidence for fish extinction in acid water indicates that reproductive failure was the causitive mechanism (Beamish et al. 1975). Reproductive failure may occur on the population level in the form of recruitment failure or on the individual level as spawning cessation.

RECRUITMENT FAILURE

Recruitment failure of fishes in acidified freshwaters of Norway and Sweden is attributed to mortality of eggs and larvae (Jensen and Snekvik 1972). A number of other mechanisms and processes could, under the influence of low pH, promote recruitment failure. These include failure of gametes to develop or function properly, failure of fertilized eggs to develop or hatch, hatching of larvae that are deformed or otherwise unfit.

Failure of Gametes to Develop or Function Properly

Beamish et al. (1975) noted that yolk protein is transported to the ovaries as complexes of calcium with phosphoproteins. The lower than expected levels of calcium in the ovaries of maturing females in acid-stressed lakes suggest that ova of effected fish may not develop normally. Ruby et al. (1977) demonstrated experimentally that depressed pH reduced the ability of flag fish (Jordinella floridae) oocytes to form mature eggs. This failure resulted from the inability of oocytes to deposit secondary yolk within the cytoplasm. There is some evidence that sperm is also adversely affected by low pH. EIFAC (1969) reported several studies which demonstrate decreased motility of carp sperm at pH levels of 6.5 and 4.5 and mortality at pH below 4.5.

Failure of Fertalized Eggs to Develop or Hatch

Mount (1973), working with fathead minnows (Pimephales promelas) and Menendez (1976) working with brook trout (Salvelinus fontinalis) demonstrated that the numbers of viable eggs produced at pH of 5.9 and 5.0, respectively were significantly less than in control populations (Table 2). Low pH has also been shown to inhibit or retard the hatching of Atlantic salmon eggs exposed after eye pigmentation had developed (Peterson et al. 1980). Although some ova were viable at the low pH levels tested, and hatching can be induced by returning the eggs to a normal pH level, a continuous decline in hatching success and viable egg production could eventually lead to the decline of the population.

Hatching of Larvae that are Deformed or Otherwise Unfit

Developing fish are influenced by a number of environmental factors. Many authors have described the effects of increased temperature or salinity on morphometric and meristic characters of fish (such as vertebrae counts and fin ray numbers Lindsey 1954; Garside 1966). The effects of low pH on the development of white suckers (Catastomus commersoni) and fathead minnows, have been described by Beamish (1972) and Mount (1973) respectively. Their studies showed that a greater percentage of fish exposed to low levels of pH developed skeletal deformities than control fish. Deformed fathead minnows that survived did not spawn.

Schindler (personal communication), describing studies of salmonids from an artificially acidified lake, noted an increase in the number of deformed fish. Deformities, particularly those associated with the vertebral column, can diminish swimming abilities thereby increasing susceptibility to predation and potentially decreasing feeding ability. The occurrence of skeletal deformities also suggest that fish reared in acidified water could develop abnormalities in other organ systems, a situation which could potentially reduce fitness (Daye and Garside 1980).

CESSATION OF SPAWNING

Several authors have attributed the decline and eventual extinction of fish in a number of La Cloche Lakes of Ontario Canada to the failure of fish to spawn (Beamish and Harvey 1972; Beamish et al. 1975; Beamish 1976; Harvey 1975, 1979). The pH at which different species ceased to spawn also differed (Table 2). Beamish et al. (1975) suggested that the inability to spawn is somehow related to calcium regulating factors associated with ovarian maturation and an increase in the protein based fraction of serum calcium. Other mechanisms that may cause spawning to cease are inhibition of spawning behavior and failure to find proper spawning habitat.

Spawning Behavior Inhibited

Daye and Garside (1976) described pH-induced histological changes that could affect courtship behavior and demonstrated that the cornea, integument, and nares of fingerling brook trout are damaged at pH 4.2 and below when exposed for 10,000 minutes (about 7 days). Such pH values have been reported during snowmelt (Schofield 1977). Slight damage to the cornea could result in spawning failure among fish species which require the perception of visual cues during courtship. Similarly, damage to the epidermal secretory cells that produce sex pheromones, or to olfactory tissues with which the pheromones are perceived, can also inhibit courtship among some fish species. The inhibition of such behavioral activity may explain the observations of Beamish (1972, 1976) that female white suckers with ripe ova failed to spawn.

Failure to Find Proper Spawning Habitat

Failure of fishes to find spawning habitat is also related to damage to the cornea and olfactory tissue. Those species that locate spawning habitats through visual and olfactory cues could be adversely affected by acidic water. Damage to olfactory tissue, such as that described by Daye and Garside (1976, 1980), could be particularly detrimental to salmonids which imprint and utilize olfactory cues in their spawning migrations.

DECLINE IN PRODUCTIVITY

A decline in production coinciding with commonly encountered stresses such as fishing or contaminent loading, could result in an unrecoverable drop in population density (Goodyear 1977). The addition of a small but continuous stress, such as could be postulated for small declines in pH, to an already stressed population could eventually bring about extinction (Goodyear 1977). This type of population response could account for the loss of fish populations in acid-stressed bodies of water that have been subjected to fishing pressure.

A number of studies have been reported which demonstrate that low pH does reduce biological productivity. Declines in growth of fish exposed to waters of low pH has been described by Beamish (1972), Menendez (1976), and Craig and Baksi (1977). Fecundity also has been shown to decrease at a rate different for that expected from the fecundity-size relationship. Evidence for acid-induced decreases in fecundity (Table 3) was provided by Mount (1973), Menendez (1976), and Craig and Baksi (1977). The relationship of declining biological production and multiple stress is one that requires a great deal of additional study.

SUMMARY

1. Many of the physiological processes in fish affected by depressed pH and the manner by which the effects are expressed have not been identified or studied.

2. Little effort has been made to assessing the effects of various periods of lethal and sublethal doses of acidity and exposure during different seasons and life stages, even though fish populations in waters that are becoming increasingly acidic will be mainly affected by periodic or episodic inputs of acid.

3. Evidence indicates that the extinction of fish populations in acid stressed systems results from pH-induced recruitment failure rather than a single catastrophic decline in pH.

4. Some evidence based on studies of acid-induced destruction of epithelial cells and gill lamellae, ion imbalance, and reduced egg viability, suggests that decreased pH could increase susceptibility to disease and physiological stress.

5. Declining numbers of forage fishes resulting from low pH could induce canabalism and predation on the young of economically and recreationally important species.

6. Decreased pH could result in degradation of benthic habitats through the growth and formation of macrophytic and fungal mats.

7. Toxic chemicals released from lake sediments, leached from a surrounding watershed and deposited directly from the atmosphere, are considered a potential hazard to fish inhabiting the affected water body.

8. Reproductive failure appears to be the major mechanism influencing the extinction of fish populations in acid-stressed water bodies.

9. Studies have indicated that recruitment failure can result from the failure of gametes to develop or function properly, from the failure of fertilized eggs to develop or hatch, or from an increase in the frequency of deformed or otherwise unfit larvae.

10. Reproductive failure may result from the inhibition of spawning behavior or failure to find proper spawning habitats.

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